Symptoms and Causes of Distorted Growth in Immature Forest Stands in Coastal British Columbia

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Symptoms and Causes of Distorted Growth in Immature Forest Stands in Coastal British Columbia

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ABSTRACT

Individual symptoms of undesirable growth form characteristics (distorted growth) in coastal Douglas-fir are presented and discussed in relation to their causes. The results of five studies are included. These studies examine the pattern of occurrence of distorted growth characteristics in relation to site ecological characteristics, genetics, and stand nutrition, age and density.

Lammas growth, sunscald, and damage by birds, insects, snow and wind are recognized as the most common causes of forks in the main stem. Forking, stem sinuosity, and excessive branchiness were most common on moist, nutrient-rich sites of the Wetter Maritime Coastal Western Hemlock biogeoclimatic subzone (CWHb). Isolated occurrances of severe dieback and/or swelling and discoloration of leading shoots are suggested to result from acute deficiencies of micronutrients, primarily boron.

Considerations involved with the recognition and management of stands affected by distorted growth are presented. Site-specific tree species selection, and control of stand density are suggested to be the most useful preventative tools while selection of trees of the best form during spacing and pruning are offered as the most viable rehabilitative measures.

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The authors thank the Science Council of British Columbia for their generosity in providing financial assistance throughout the course of this study. The support of the Vancouver Forest Region of the B.C. Ministry of Forests is also gratefully acknowledged. The authors are indebted to Canadian Forest Products Ltd. for their support of the study on the occurrence and pattern of distorted growth.

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INTRODUCTION

Poor growth and growth form in immature Douglas-fir (Pseudotsuga menziesii) stands and, to a lesser extent, western hemlock (Tsuga heterophylla), western redcedar (Thuja plicata), and Pacific silver fir (Abies amabilis) on some sites within a wet, cool mesothermal climate have become a serious concern of foresters in coastal southwestern British Columbia. The questions most often asked are: What are the causes of various forms of "distorted growth"? What will be the effect of distorted growth symptoms on the final crop? What treatments are available for the prevention and/or rehabilitation of distorted growth problems?

Distorted growth, growth disturbances, growth deformities, and several other phrases have been used to describe characteristics of undesirable form and/or growth performance. Several studies have examined these growth problems, dealing with the causes and patterns of occurrence of specific distorted growth symptoms, and examining these symptoms in relation to stand nutrition, genetics and genotype-environment interaction, stand age and density, physical damage, and major site factors.

Most immature forest stands display some undesirable growth characteristics. Foresters must be able to decide (1) when these characteristics constitute a problem, (2) what factors are responsible for their occurrence, (3) what management options are available for treatment of the problem(s), and (4) which is the best treatment for a given problem. This report is intended to assist foresters in making these decisions.

This report presents the results of several studies, each carried out to explain a specific aspect of distorted growth. When combined, the findings of these studies should provide an integrated picture of the factors responsible for growth deformities and give insight into the management options available at this time; no claim is made that the picture is complete.

SYMPTOMS AND PRESUMED CAUSES OF DISTORTED GROWTH[1]

Specific symptoms of distorted growth can be the result of one or several causes. Symptom severity can be controlled by yet another set of factors. Attempts to define when a growth trait becomes a symptom of distorted growth are also made difficult by the fact that the expression of most symptoms generally occurs as a relatively continuous gradient with no convenient interruptions. However, symptoms of distorted growth can be described, and their causes identified. The degree to which they constitute a problem will depend on their severity of expression and the management objectives for each stand.

Most symptoms of distorted growth start during development of the apical shoot. Normally, forking, crooking, sinuosity, and branching are initially determined during the first growing season at that node. Further growth usually determines the persistence and severity of these symptoms. As it is not always possible to examine the leader and upper stem in older stands, the causes of distorted growth symptoms in their more mature phases are often more difficult to determine.

LEADER

Absent, Damaged, or Dead Apical Bud (Figure 1)

Death and/or damage to the apical bud can be caused by birds, animals, insects, frost, herbicides, and/or physical forces such as ice and wind. This can result in forks, upwardly inclined branches, and crooks in the main stem, any of which will reduce annual height increment. Forks resulting from apical bud problems often have a "Y" shape; crooks are usually of a minor nature with little persistent detrimental effect.

Broken Leader (Figures 2 and 3)

Broken leaders are usually caused by birds (grouse, pigeons, and crows), squirrels, wind, and snow. This results in a loss of annual height increment and crooks or forks in the main stem. Broken leaders are most common on high productivity sites where trees have large annual height increments. Breakage usually occurs while the leaders are succulent. Forks often have a less acute-angled "U" shape.

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[1] Based on Carter, R.E., G. Hoyer, and C. Weber. (1986).

FIGURE 1. Early and late symptoms of absent, damaged, or dead apical bud.

FIGURE 2. Early and late symptoms of leader breakage.

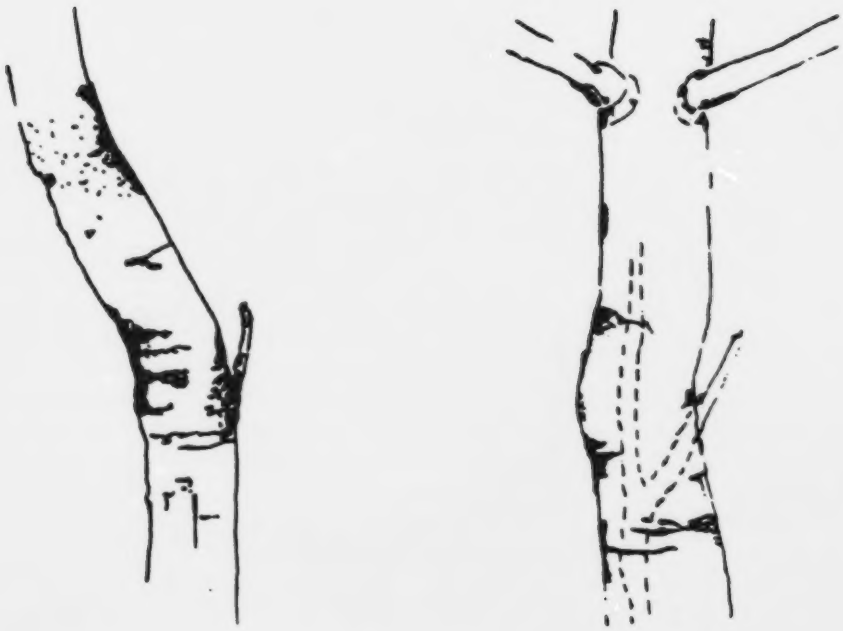

FIGURE 3. Late symptoms of crooking in the main stem.

Dead Leader (Figures 4 and 5)

Frost, drought and heat injuries, insect damage, and/or micronutrient deficiencies can all result in leader damage. Damage caused by frost and micronutrient deficiencies is often restricted to leading shoots which usually remain visible following dieback. Lateral shoots then take over as leaders, thereby creating a fork or crook in the main stem. Insect damage (usually by Dioryctria abietivorella or Zieraphera hesperiana) tends to be limited to one or two leading shoots. Drought and/or heat injury generally occur during hot dry summers, especially in trees with exceptional annual height increments growing on moist sites. Drought injury often results in defoliation of the upper one to three whorls and can result in a dead top. Repeated leader dieback can result from any of the above causes; and can cause a serious loss of height growth creating a "ceiling effect" with all the trees in the stand having a rounded or flat top.

FIGURE 4. Defoliation and dieback of the leader and uppermost whorls.

FIGURE 5. "Ceiling effect" caused by loss of annual height increment, the result of repeated leader dieback in the Brittain River Valley.

Discoloured or Swollen Leading Shoots (Figures 6 to 9)

Sunscald, heat injury, and nutrient deficiencies can also produce a reddish-brown discoloration of leading shoots. With sunscald, this discoloration is usually limited to the southwest side of leading shoots. This may result in leader dieback, although crooking or curling is more usual, and is often severe enough to seriously weaken the stem, increasing susceptibility to snow press or other sources of physical damage. Severe micronutrient deficiencies (most likely boron, possibly in combination with other nutrient elements) tend to have more universal symptoms, affecting both leaders and branch tips. The bark may have a reddish-brown discoloration and often appears stretched and swollen. Symptoms may occur repeatedly, resulting in stunted, bushy trees with no main stem.

Sinuosity, Crooking, and Curling (Figures 10 and 11)

The term sinuosity is usually applied to single or multiple sweeping curves or bends occurring in the internodes of the main stem. Sinuosity appears to be a heritable trait, occurring most often in rapidly growing trees, especially those growing on moist sites. If the curves or sweeps are only slight, trees can overcome their initial poor form without significant permanent loss of form; however, if severe, the poor stem form may persist, resulting in an undesirable increase in compression wood formation. This can seriously weaken the tree, increasing the possibility of breakage during storms or snow load.

Crooking is a form of sinuosity which occurs when a lateral takes over as the main stem, usually after the terminal bud or leading shoot has been damaged. Crooks normally originate at branch whorls rather than in internodes. Curling often occurs as a result of damage to cambial tissues on one side of the stem, frequently caused by insect larvae (possibly Dioryctria abietivorella) chewing the succulent shoot surface, sunscald or heat injury, or some other physical process. Growth and structural strength are then impaired on this damaged side of the stem and the stem develops a curl or crook. Geotrophism causes the stem to curl again as it returns to a vertical position.

Multiple Leaders (Figures 12 and 13)

The most frequent cause of forks and multiple leaders is lammas growth. Lammas growth is an abnormal burst of late-season shoot growth from the opening of recently formed buds, which is not expected until the

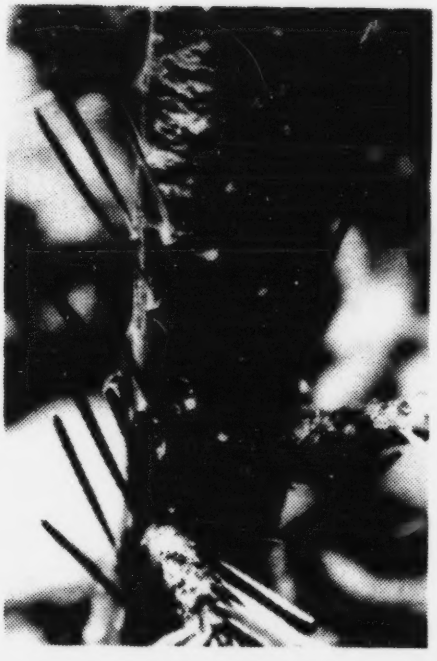

FIGURE 6. Reddish-brown discoloration of leading shoots.

FIGURE 7. Swollen leading shoots with reddish-brown discoloration thought to be caused by a severe boron deficiency.

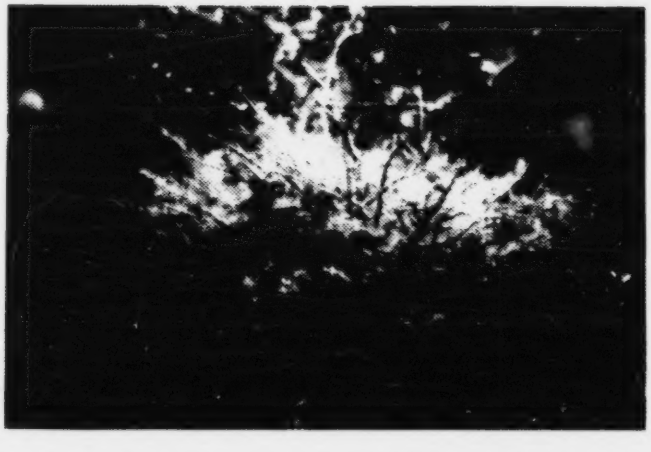

FIGURE 8. Stunted, bushy tree with multiple leaders and dieback caused by a severe boron deficiency in the Skwawka River Valley.

FIGURE 9. Effects of repeated severe dieback beginning at approximately age 12 in a 30-year old Douglas-fir stand in the Brittain River Valley.

FIGURE 10. Sinuosity of the main stem in immature Douglas-fir.

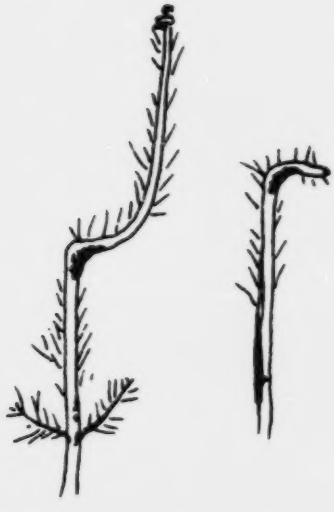

FIGURE 11. Early and late symptoms of crooking and curling of the main stem in response to cambial damage.

FIGURE 12. Late-season flushing of lateral buds at the base of the still inactive terminal bud.

FIGURE 13. Fork or ramicorn branch caused by a persistent lateral lammas shoot. (Note whorl on branch close to the main stem.)

following year. Elongation of lateral buds at the base of the still inactive terminal bud often results in lateral branches that grow in an upward direction and compete with the leader. These lateral lammas shoots can be identified by the presence of an additional node on the branch, usually situated close to the main stem. Lammas growth is most common in young trees and appears to be under strong genetic control. It is also strongly influenced by growing-season soil moisture and nitrogen availability.

Multiple leaders can also occur if the terminal shoot loses apical dominance. This is relatively rare, usually restricted to high productivity sites. To date, no specific cause has been identified. Competition between lateral (lammas) shoots and the terminal shoot can result in many serious deformities such as multiple leaders and forks in the main stem, ramicorn branches, acute branch angles, and poor stem form.

STEM FORM

Double Whorls (Figures 14 and 15)

Double whorls are a result of lammas growth involving the terminal and lateral buds. This flush results in a second branch whorl being formed in one growing season, separated from the first branch whorl by a relatively short internode. The main symptom is an increase in branch number. If elongation of the terminal bud is minimal, it often appears as though there is an abnormally large number of branches at the whorl. Lammas growth involving the terminal bud is not normally a serious problem.

Excessive Branch Size and Persistence (Figure 16)

Branch diameter and persistence are determined by stand density and structure, growth rate, and genotypic variation between individual trees. Douglas-fir is not a good self-pruner, with its branches being relatively resistant to decay fungi. Knot size and branch persistence increase with branch diameter. No exact size or period of years can be given to define when branch size or persistence become undesirable; this will depend on the expected use of the final product and economic considerations.

Excessive Branch Angle

Douglas-fir normally has a branch angle of approximately 60° from vertical. As this angle becomes steeper, the cross-sectional area of the branch increases at the branch-stem interface. This increases knot size. Branch angle has a strong genetic component but also appears to be steepest in fast-growing trees on moist, nutrient-rich sites.

Swelling of the Stem at Branch Nodes (Figures 15 and 16)

Swelling of the stem at branch whorls is primarily a function of branch number and size, usually increasing as the number and size of branches increase. While there is a genetic component to these branching characteristics, the environmental component is believed to be much more important; lammas growth and low stand density are often responsible for excessive branch number and size. Swelling of the stem at branch whorls increases the number of years following natural or mechanical pruning before clear wood is produced.

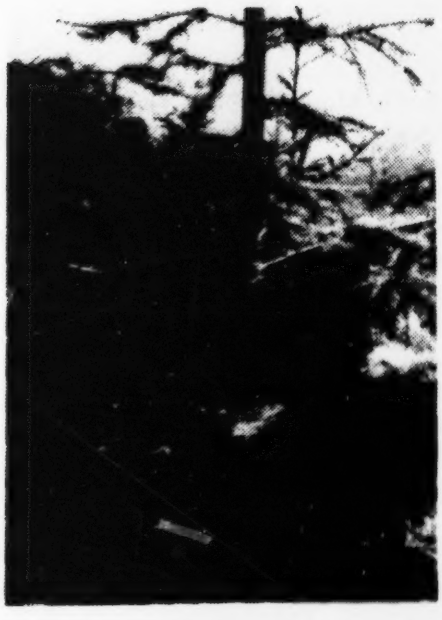

FIGURE 14. Double whorl caused by lammas growth involving terminal bud.

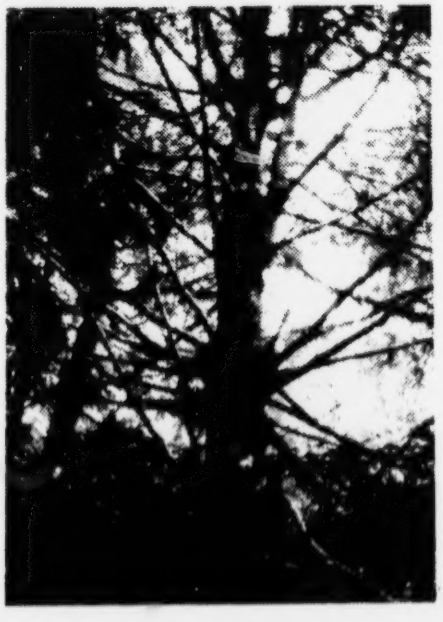

FIGURE 15. Abnormally large number of branches caused by double whorls resulting from lammas growth.

FIGURE 16. Excessive branch size due to low stand density.

FIGURE 17. Fasciated leader in young Douglas-fir. (Needles were removed for the photo).

Flattened or Ribbon-Like Leading Shoots (Figure 17)

Douglas-fir will occasionally have flattened or ribbon-like leading shoots, the phenomenon being known as "fasciation". It may be the result of a virus. Fasciation normally occurs in small localized areas, rarely causing a significant problem.

Snow Damage (Figure 18)

Heavy snow loads can cause direct breakage of leaders and branches, or, in stands subject to repeated heavy snow fall, recumbent trees with little or no upward tendency. Snow press can also cause breakage of the main stem, and occasionally uprooting of large clumps of trees within a stand. This is normally the consequence of excessively high stocking levels with poor diameter growth. Periodic damage in plantations subject to heavy snowfall is expected, mostly resulting in broken branches and forked stems.

HERBICIDES (Figure 19)

Growth disturbances involving serious top deformation and sometimes extreme sinuosity are occasionally found along roadsides sprayed with herbicides. Symptoms include dead and/or swollen leaders, loss of dominant main stem, and extreme sinuosity of the main stem and branches. Knowledge of the location of treated roadsides and recognition of symptoms are important to avoid confusion with the symptoms of other causes.

FIGURE 18. Broken branches caused by heavy snow load.

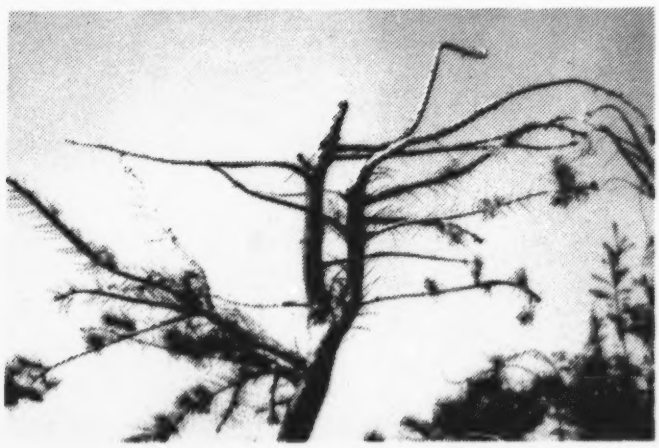

FIGURE 19. Growth disturbance symptoms caused by herbicides.

OCCURRENCE AND PATTERN OF DISTORTED GROWTH

SPECIES, SITES, AND AREAS AFFECTED

Distorted growth is most common in immature Douglas-fir plantations, however, several symptoms presented in the previous sections have been found in western hemlock, western redcedar, and Pacific silver fir stands (e.g., broken leaders, sinuosity, excessively large persistent branches, and symptoms of nutrient deficiencies).

Distorted growth occurs over a wide range of sites. Douglas-fir appears to be most susceptible to distorted growth on sites where it did not grow originally, especially on moist soils in wet, cool mesothermal climates. Douglas-fir can be affected in drier climates but symptoms (especially the effects of lammas growth) are usually less persistent. No accurate assessment of the areal extent of stands showing varying degrees of distorted growth has been made to date.

OCCURRENCE AND PATTERN OF DISTORTED GROWTH ON T.F.L. 37[2]

The objective of this study was (1) to examine the causes and pattern of occurrence of distorted growth symptoms in Douglas-fir plantations of the Nimpkish Valley; and (2) to explain the pattern and severity of individual symptoms in relation to soil lithology, soil moisture regime, and stand age.

Study Area

The study was carried out in the Vancouver Island Drier and Submontane Windward Wetter Maritime Coastal Western Hemlock biogeoclimatic variants in the Nimpkish Valley (CWHa1 and CWHb1). The area receives 1900-3000 mm of precipitation per year; at lower elevations most of this falls as rain. Forest soils in the CWHa1 variant normally experience a summer moisture deficit between mid-July and late August.

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[2] Based on Carter, R.E. and A. Willcocks. 1985. Distorted growth on T.F.L. #37: Causes and pattern of occurrence. Contract Res. Rpt. (Sect. 88) to Canadian Forest Products, Ltd., Englewood Logging Div. 51 pp.

Glacial till is the dominant unconsolidated soil parent material on the valley side slopes and bottoms, and usually occurs as a mantle of varying thickness over bedrock. Fluvial and glacio-fluvial sediments are extensive adjacent to major rivers, with alluvial and colluvial materials often coalescing at the base of the steep slopes. The three major bedrock types influencing the lithology of soil parent materials in the study area include the following (Howes 1981):

1. Intrusives (granitics)
   - Island Intrusives: granodiorite, granite, quartz monzonite;

2. Volcanic extrusives (volcanics)
   - Karmutsen Formation: basalt lava, pillow lava, and breccia
   - Bonanza Group, Sicker Group, late Tertiary Volcanics: basaltic to rhyolitic lava, tuff breccia, minor greywacke, and conglomerate;

3. Sedimentary (limestone)
   - Quatsino and Parson Bay Formation: limestone, calcareous siltstone, and shale.

Douglas-fir occurs naturally throughout the Nimpkish Valley up to approximately 900 m elevation on southerly exposed slopes and to approximately 600 m on north and northeast aspects. The most productive stands are found on fresh and nutrient-rich soils. Old-growth Douglas-fir stands, often over 500 years old, occasionally have individuals over 80 m in height, with average stand heights of over 60 m not uncommon. Pure stands of Douglas-fir are common, with western redcedar and western hemlock usually becoming a significant component during later successional stages.

Methods

The study examines 15 measured and 5 calculated growth performance, stem form, and branching variables within 20 trees per plot for 24 plots (Table 1). The study is a 3 x 3 design replicated across three age classes. The two strata are soil parent materials of three lithologies and three generalized soil moisture regimes. One level of one stratum is absent, resulting in 24 plots rather than 27 (i.e., no plantations within the older age class could be found on limestone parent materials).

The lithology stratum represented general differences in soil base status, texture, and coarse fragment content. The three lithologies are those identified earlier. These parent materials were located using surficial geology maps (Howes 1981). Both pleistocene glaciation and more recent fluvial and colluvial processes have resulted in many soils being derived from parent materials of mixed lithology. Consequently, the

TABLE 1. Measured and calculated variables used in the study

Measured variables:

1. dbh (at 1.3 m);
2. height to the base of the live crown;
3. stem diameter, taken in the centre of whorls 4, 5, 6, 7, and 8 (counted from base of tree);
4. stem diameter 10 cm above whorls 4, 5, 6, 7, and 8;
5. number of primary branches in whorls 4, 5, 6, 7, and 8;
6. number of secondary branches in whorls 4, 5, 6, 7, and 8;
7. mean diameter of primary branches in whorls 4,5,6,7, and 8;
8. presence or absence of lammas growth at whorls 4, 5, 6, 7, and 8;
9. number of branches in lammas whorl associated with whorl 4, 5, 6, 7, and 8 (if present);
10. mean diameter of lammas branches in whorls 4, 5, 6, 7, and 8 (if present)
11. presence or absence of ramicorn branches at whorls 4, 5, 6, 7, and 8 (includes lammas laterals);
12. total number of forks in the main stem;
13. total number of double whorls in the main stem;
14. total number of ramicorn branches in the main stem;
15. subjective index of stem sinuosity (1 to 4; straight to very sinuous);
16. number of leaders currently on main stem.

Calculated variables:

1. total branch number at whorls 4, 5, 6, 7, and 8;
2. total number of double whorls in whorls 4, 5, 6, 7, and 8;
3. total number of ramicorn branches in whorls 4, 5, 6, 7, and 8;
4. ratio of diameter at the centre of whorls 4, 5, 6, 7, and 8 to mean stem diameter above and below each whorl;
5. total surface area of primary and secondary branches at whorls 4, 5, 6, 7, and 8 (πr^2 [total no. of branches at whorl]);

lithology classes were classified subjectively and interpreted as general indicators of soil nutrient regime.

Regional climate (represented by biogeoclimatic variants) and topographic and soil features were used in conjunction with indicator plant species to identify three general moisture regime classes. These general classes, referred to as dry, fresh, and moist, respectively (Klinka et al. 1984), were used as the second stratum in the data analysis.

The lithology and soil moisture strata served as a basis for organizing the results of statistical analysis. It must be recognized that both of these strata are subject to considerable within-stratum variability and that interpretations should be limited to the identification of factors influencing the pattern of occurrence of distorted growth symptoms rather than to the statistical significance of individual results.

The three age classes used are 8-13, 14-18, and 19-25 years. These age classes were chosen for the following reasons:

1. the greatest proportion of second-growth Douglas-fir plantations were found within these age classes;

2. the range in age was felt to be sufficient for the examination of the occurrence and persistence of several distorted growth symptoms with age; and

3. the trees were old enough to reflect the conditions of their environment, while still being small enough for the accurate measurement of their upper crown characteristics.

Within each plantation the portion most homogeneous in topography, stocking, and surface vegetation was located for sampling. Ten dominant and co-dominant trees were then selected systematically along each of two randomly selected transects. Trees were excluded if they were growing on road-cast materials, if they showed obvious signs of pathological damage, or if they were planted on improper microsites (e.g., decaying wood or standing water).

Results

Tree Height and DBH

Tree height and diameter growth were examined in relation to the strata to relate the occurrence of specific distorted growth symptoms to growth rates. Tree height and diameter growth were significantly different between both lithology and soil moisture strata ($p < 0.01$). Soil moisture accounted for up to 52% of the total variation in height growth and 48.5% of variation in diameter at breast height (dbh), although this appears to decrease with age. Trees growing on the granite soils had the greatest total height and dbh within each age class.

Number of Branches

The total number of branches per whorl is determined by the number of lateral buds formed on the terminal shoot in the previous year. The

success of bud flushing and shoot elongation can also vary from year to year as a result of climatic variation and occasionally physical damage by wind, snow, insects, and birds. As a result, some confounding of relationships between the strata and/or year of whorl establishment may have occurred. However, since the sampled whorls developed during different years from one plot to the next, this confounding should not create a consistent bias and should be overcome by adequate replication.

Branch number appeared to be related to lithology, particularly up to whorl 6 (Table 2). Trees with the greatest number of branches were found on granitic soils (Table 3). These sites also supported the fastest growing trees of the plots studied. The smallest and least branchy trees were on the limestone soils. Although differences in total branch number were not consistently significantly different between the soil moisture regime classes, total branch number consistently increased with increasing soil moisture. Total branch number also increased as the trees grew older (i.e., from whorl 4 to 8) (Table 3).

Branch Diameter

Average branch diameter indicates knot size and branch persistence. When related to branch number and the ratio of stem swelling at each whorl[3], an index of stem quality can be estimated. Branch diameter appears to be influenced by different factors between whorls and age classes. Lithology accounted for the greatest amount of variability in the early whorls (4 and 5) in age classes 1 and 2, while soil moisture became increasingly more important in the progression from whorl 4 to 8 in these age classes. The interaction between soil lithology and soil moisture was the most significant factor in age class 3 and became increasingly important in the older whorls. Branch diameter increased along the soil lithology gradient from granitic to volcanic to limestone and with increasing soil moisture.

Branch diameter increased with age class for each whorl (Figure 20). The increase in branch surface area with age class is greatest in the upper whorls which are more likely to still be carrying photosynthetically active foliage. The lower branches, although smaller in diameter, are still increasing in size in all age classes, indicating that natural branch mortality may be somewhat slow. This may result in large, persistent branches. These branches became larger and more persistent from limestone to volcanic to granitic soils, and with increasing soil moisture. The

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[3]The ratio of the stem diameter within each of whorls 4 to 8 to the mean stem diameter at each whorl (calculated as the mean of the diameters taken 10 cm above and 10 cm below each whorl).

TABLE 2. Percent of variation in total number of branches attributable to each stratum

Stratum	Whorl 4	Whorl 5	Whorl 6	Whorl 7	Whorl 8
Lithology (L)	24.5[1]	23.4[1]	16.4[1]	4.7[1]	1.3[2]
Soil moisture (SM)	0.6	0.2	0.7	3.4	4.2
L x SM interaction	3.2[1]	3.9[1]	0.7	4.3[1]	2.2[2]

[1] Significant at $p < .01$.
[2] Significant at $p < .05$.

TABLE 3. Mean and standard deviation[1] for total number of branches for each parent material and soil moisture class

Parent material	Whorl 4	Whorl 5	Whorl 6	Whorl 7	Whorl 8
Granitics	5.9 (2.3)	6.8 (1.9)	7.1 (1.8)	6.8 (1.8)	6.7 (1.7)
Volcanics	4.8 (2.1)	6.0 (1.7)	6.4 (1.5)	6.4 (1.5)	6.4 (1.6)
Limestone	2.4 (1.8)	4.1 (2.3)	4.9 (2.1)	5.7 (2.2)	6.2 (1.9)
Dry	4.4 (2.4)	5.7 (2.3)	6.1 (2.0)	6.1 (1.7)	6.2 (1.7)
Fresh	4.6 (2.4)	5.9 (2.0)	6.3 (1.9)	6.1 (1.9)	6.2 (1.7)
Moist	4.8 (2.7)	5.9 (2.4)	6.5 (2.2)	6.8 (2.0)	6.9 (1.7)

[1] Standard deviations are in parentheses.

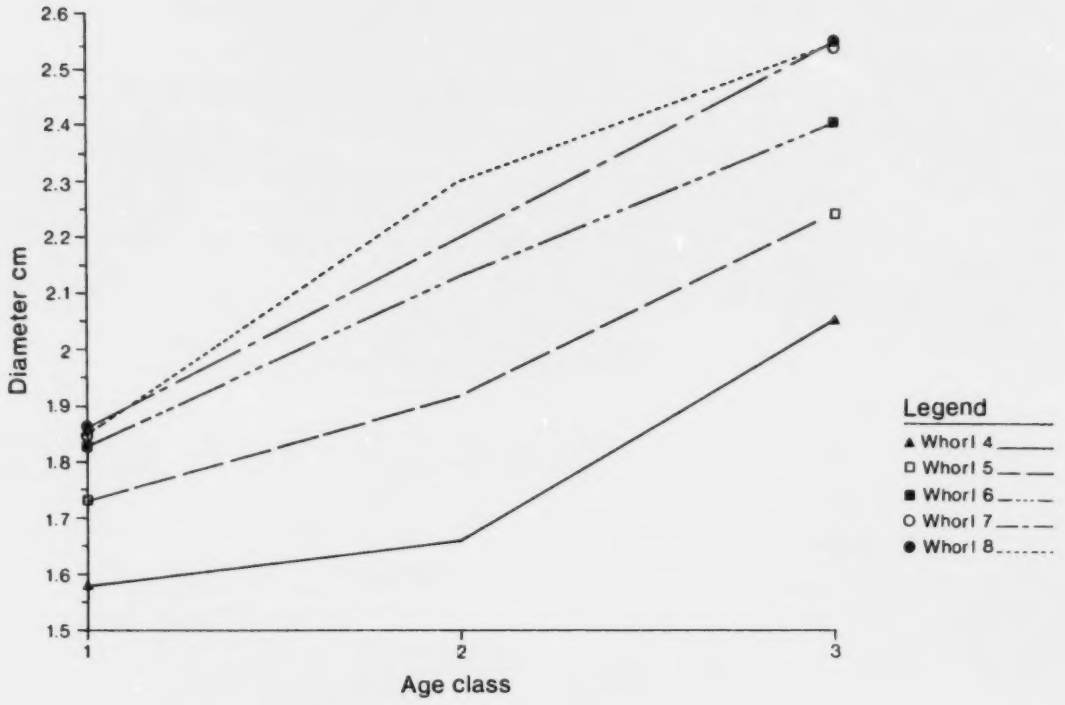

FIGURE 20. Relationship between branch diameter and age for each whorl.

total number of branches also increased along these same environmental gradients indicating that branch size and branch number are closely related.

Ratio of Stem Diameter to Whorl Diameter

This variable is a relative measure of stem swelling at each whorl. Neither the strata nor their interaction was able to consistently account for much of the variability in this ratio. The ratio does not accurately indicate stem swelling at branch whorls when compared among whorls or age classes, because it declines with increasing stem diameter (i.e., ratio at whorl 4 is less than whorl 8 and in age class 1 is less than age class 3). However, even though the ratio declines, the actual difference in diameter increases as stem diameter increases (Table 4). This diameter difference, when considered with branch diameter, can be used as an indication of how much radial increment will be required after pruning, before clear wood will be produced.

The ratio was significantly correlated with total branch surface area at each whorl (Table 5), supporting the hypothesis that stem swelling is a function of branch number and size -- with stem swelling increasing as branch number and size increase.

TABLE 4. Increase in stem diameter at whorls 4 to 8 by age class

Age class	Branch whorl	Mean stem diameter (cm)	Mean ratio	Diameter increase (cm)
1	4	4.00	1.08	0.03
	5	3.70	1.11	0.41
	6	3.35	1.13	0.45
	7	2.50	1.20	0.50
	8	1.65	1.18	0.29
2	4	7.45	1.05	0.90
	5	7.30	1.07	0.54
	6	7.15	1.09	0.62
	7	6.90	1.09	0.64
	8	6.55	1.18	0.56
3	4	14.95	1.04	0.66
	5	14.25	1.06	0.91
	6	13.75	1.07	0.94
	7	13.00	1.08	0.99
	8	11.80	1.08	0.90

TABLE 5. Correlation coefficient[1] for correlation of total branch area to ratio of stem swelling for whorls 4 to 8

Age class	Whorl 4	Whorl 5	Whorl 6	Whorl 7	Whorl 8
1	0.31	0.14	0.13	-0.04	-0.19
2	0.58	0.56	0.28	0.34	0.33
3	0.55	0.40	0.43	0.47	0.36

[1] r is significant at $p < .01$ when < 0.208; at $p < .05$ when < 0.164.

Forking in the Main Stem

The total number of forks in the main stem did not appear to be significantly related to either lithology or soil moisture. This measurement was extremely variable, with an average coefficient of variation of 513%. This implies that a much larger sample size would be necessary to predict the mean value with an adequate level of precision and accuracy. However, if the mean values are examined as presented, several important comments should be made. Firstly, on the most severely affected sites the percentage of trees with forks in the main stem reached a maximum of 10% (Figure 21). When the relatively young age of these trees is considered, it must be assumed that a dominant single stem will be regained in at least some of these trees, with only minimal damage to stem form. Second, the total number of forks in the main stem did not increase with age; in fact, it decreased, suggesting that some forks had been overcome. The average percentage of trees with forks for age classes 1 to 3 was 5.2, 4.5, and 4.4, respectively. Forks in the main stem did not appear to represent a significant threat to the commercial variability of the final crop in any of the stands examined.

Lammas Growth

Of all whorls examined, 1.8% showed evidence of lammas growth (as recognized by the occurrence of double whorls). This frequency is so low that identification of significant trends between strata is difficult.

Lammas shoots initiated from lateral buds at the base of the still inactive terminal bud were more common than lammas growth involving the terminal bud, having an average frequency of 3.2% and ranging as high as 7.6% of all whorls being affected. The occurrence of lammas growth involving only lateral shoots was significantly higher on moist and limestone soils when measured across all the whorls, and on the moist sites across all whorls. No trends appeared to be obvious in relation to increasing whorl age (Figure 22).

The occurrence of lammas growth varied significantly between trees within a stand. This may be due to microsite variation or, more likely, to genotypic variation between trees. All of the plantations studied were of a local provenance. Results of a pilot study carried out in the Nimpkish Valley in 1983 show that trees with multiple occurrence of lammas shoots had significantly higher foliar N concentrations and contents than trees grown on the same site with no occurrences of lammas shoots (Table 6).

FIGURE 21. Percentage of trees with forks in the main stem for each lithology and soil moisture regime across the 3 age classes.

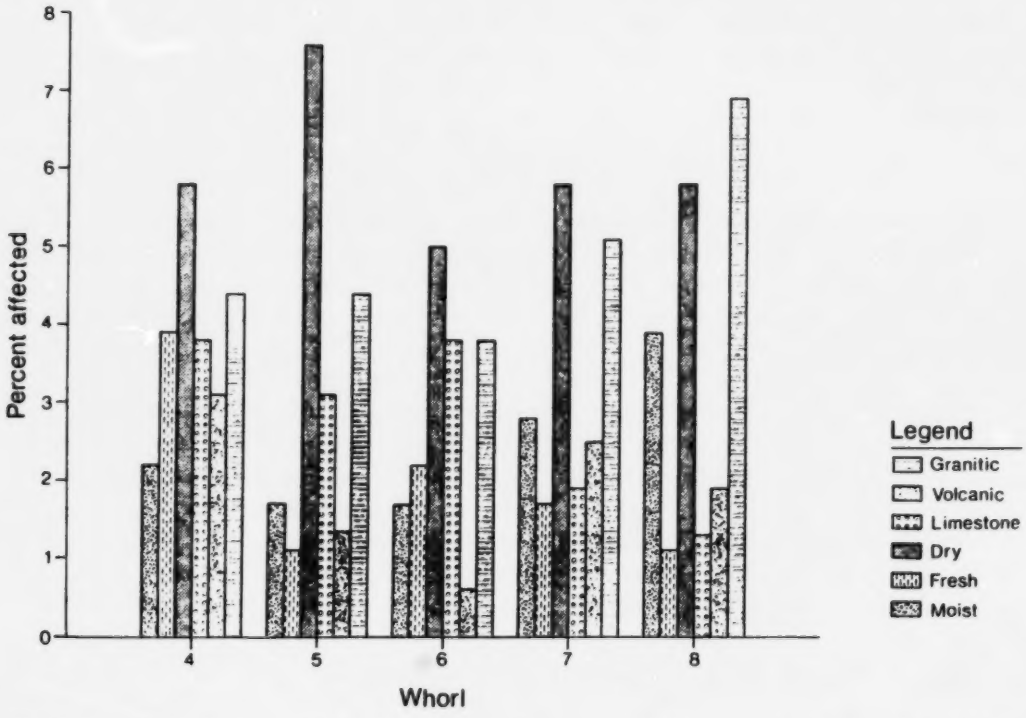

FIGURE 22. Frequency of lammas growth involving only lateral buds in whorls 4 to 8.

TABLE 6. Foliar chemistry[1] of Douglas-fir trees with and without multiple occurrences of lammas growth

Stand	Weight/100 needles (mg)	N	P	K	Ca	Mg	SO_4-S	Active Fe	Mn	Cu	Zn	B
		----------		(%)	----------		----------		(ppm)	----------		
Q 70 G[2]	634	1.18	0.15	0.46	0.21	0.08	115	70	640	5	22	27
Q 70 P	627	1.37	0.13	0.65	0.28	0.09	125	125	290	6	19	20
NE 1 G	625	1.25	0.15	0.62	0.20	0.08	245	70	620	7	18	27
NE 1 P	629	1.48	0.17	0.68	0.21	0.08	245	75	680	5	19	27
WF 10 G	547	1.07	0.23	0.60	0.26	0.11	350	55	670	5	20	22
WF 10 P	624	1.16	0.19	0.58	0.27	0.10	190	60	415	7	20	29
RO 50 G	608	1.24	0.17	0.63	0.27	0.09	195	80	435	6	20	25
RO 50 P	704	1.41	0.18	0.61	0.25	0.09	195	135	410	8	22	21

[1] Sample represents a composite of samples from 15 trees.

[2] G = trees with no lammas growth; P = trees with multiple lammas growth.

Summary

After analysis of the occurrence and persistence of specific factors known to affect or cause distorted growth symptoms, several significant trends could be observed. Tree height, diameter at breast height, total number of branches at each whorl, branch diameter, and swelling at branch whorls all appear to be related, increasing or decreasing together and in relation to the same environmental gradients. In general, as stands were sampled along the lithology gradient (from limestone to volcanic to granitic) and along the soil moisture gradient (from dry to moist soils) growth form tended to become less desirable. Lithology appears to have the greatest influence on tree growth and form when the trees are relatively young (i.e., age classes 1 and 2). As trees or stands become older this influence becomes less evident, with soil moisture accounting for a greater amount of the variability in the occurrence of distorted growth symptoms than lithology. In general, trees with the best growth form were found on dry limestone soils, while trees with poorest form were found on moist granitic soils.

Branch number, branch size, and swelling of the stem at branch whorls increased up the stem from whorl 4 to 8. Increasing branch size results in an increase in branch persistence following natural branch mortality. This increases knot diameter and longevity.

Lammas growth involving both terminal and lateral buds is primarily a concern in relation to branch number. No obvious trends were evident in relation to the occurrence of lammas growth and soil lithology or moisture, tree age, or position in the tree. Lammas growth may be slightly more common on moist soils. Double branch whorls resulting from lammas growth occurred in 1.8% of the whorls examined in trees across all stands.

Lateral branches resulting from lammas growth when the terminal bud did not flush were slightly more common, occurring in 3.2% of the whorls examined in trees across all stands. These lateral lammas shoots were most common in trees growing on moist limestone soils. In general, lammas growth appeared to be most common in fast-growing trees.

Forks in the main stem were most common in stands on moist soils in age class 2 (10%) while the average over all sites was approximately 4.5%. In younger age classes some forks may not persist, resulting in little permanent damage to the main stem. This was evident by a reduction in the number of forks as age increased.

LATE-SEASON FLUSHING[4]

Late-season flushing (lammas growth) is likely the single most important cause of distorted growth. A review of the literature shows that it often results in double whorls with an associated increase in branch number and shortened branch internodes. Lammas shoots originating from lateral buds directly below the terminal bud appeared to be responsible for most of the more serious deformities such as forks to the main stem, ramicorn branches, acute branch angles, increased branch size, and poor stem form. These symptoms are usually caused when lateral buds flush, while the terminal bud remains dormant, resulting in competition for apical dominance between these laterals and the terminal shoot. Frost damage to these late-season shoots may also result in distorted growth (Rudolph 1964; Moulalis 1975; Halle et al. 1978).

Lammas growth has been identified as early as the 3rd century and studied since the middle of the 18th century (Studhalter 1955). Many causes have been postulated from observations and research. Most of these causes are related to one or more of the following three themes. The first is generally related to an unusually favourable soil water supply in the late summer, often following a period of temporary drought (Busgen and Munch 1929; Carvell 1956; Rudolph 1964). Bell (1957) found that the occurrence of lammas shoots in Sitka spruce (Picea sitchensis) was related to the previous season's weather, while for Douglas-fir, rainfall patterns of the current season appeared to be most important. Alden (1971) found a similar relationship to previous years weather in Scots pine (Pinus sylvestris).

The second cause appears to be related to seed origin and genetic control of late season shoot formation. Trees of southern provenances planted in more northern latitudes may experience an increase in lammas shoots due to changed photoperiod (Bodganov 1931; Jump 1938; Downs and Borthwick 1956; Vaartaja 1957; Rudolph 1964; Marcet 1975). Moulalis (1975) found a similar difference between provenances of Norway spruce (Picea abies), with high elevation provenances showing less lammas growth than low elevation provenances planted at higher elevations. Provenance studies with Sitka spruce (Wood and Lines 1959) and Douglas-fir (Walters and Soos 1961) have shown differences in the frequency of occurrence of lammas growth among populations.

The final theme falls loosely under nutrition. Several researchers have found the occurrence of lammas shoots to be related to stand nutrition

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[4]Based on Klinka, K. and R.E. Carter. 1984. Rehabilitation of second growth plantations showing distorted growth in the Wetter Maritime Coastal Western Hemlock biogeoclimatic subzone. Annual Res. Rpt. to Science Council of B.C.

and tree vigour (Busgen and Munch 1929; Sokolov and Artyushenko 1957; Walters and Soos 1961; Smith and Allen 1962; Walters and Kozak 1967; Wareing 1974). Busgen and Munch (1929) observed that heavy manuring promoted lammas growth. Carvell (1956) and Walters and Soos (1961) found that lammas growth occurred most commonly on the high productivity sites for the growth of the species under consideration. Smith and Allen (1962) found that up to 79% of 2-year-old Douglas-fir seedlings supplemented with organic or inorganic fertilizers had a second flush. A significant relationship was shown between lammas growth and parent tree, rate of fertilizer application, and tree height. Walters and Kozak (1967) found certain fertilizer treatments influenced late-season flushing. Fertilization with 4 g of ammonium nitrate (33-0-0) per tree (applied four times over two growing seasons) significantly increased the number of lammas shoots. Of seven fertilizers applied, all except the two non-N fertilizers stimulated a significant increase in lammas growth. However, the results were quite variable suggesting that environmental influences may exceed the effect of some treatments (Walters and Kozak 1967).

Several other causes for late-season flushing have been postulated and exceptions to the above hypotheses likely exist. However, lammas growth is most common in young plantations (Walters and Soos 1961), likely occurring as a result of the combined effects of one or more of these causes.

NUTRITIONAL ASPECTS OF LATE-SEASON FLUSHING

Introduction

In the Vancouver Forest Region, lammas growth occurs most often in Douglas-fir stands growing on high productivity sites located in valley bottoms, often under the influence of seepage. Foliar N concentrations and contents of Douglas-fir are often relatively high. These sites appear to have relatively large amounts of available nitrate- and ammonium-N and seepage inputs of other nutrients as indicated by the high occurrence and cover of Tiarella trifoliata, Polystichum munitum, Athyrium filix-femina, Rubus spectablis, and Sambucus racemosa. These sites are also likely to experience very favourable soil moisture conditions during early to mid-August, the period when lammas growth normally occurs. In some of these plantations the trees are of a local provenance; however, in many plantations the exact seed origin is unknown. Many seedlings have been planted on sites previously supporting western hemlock, western redcedar, and Pacific silver fir. As a result, all three of the hypotheses presented earlier may be involved in controlling the occurrence of lammas growth. It was decided to initiate a pilot study: 1) to examine whether tree nutrient status, measured by foliar analysis, could be related to the occurrence of lammas growth involving both leaders and laterals, and 2) to aid in the design of future studies on this topic.

Methods

The study was carried out in the southwestern portion of the University of British Columbia Research Forest near Haney, B.C. (49° 17'N; 122° 36'W). The forest is located within the Pacific Ranges Drier Maritime Coastal Western Hemlock biogeoclimatic variant (CWHa2). The study site has an elevation of 145 m with a west-southwest aspect and a slope of 8%. The dominant soil is a Gleyed Humo-Ferric Podzol, with sandy loam texture, derived from mixed glaciofluvial and glaciomarine deposits. Gleying occurs at approximately 42 cm with no roots below this depth. Most roots are in the Ap and Bf horizons of the upper 30 cm.

The study site was burned, cleared of stumps, and ploughed to form a relatively homogeneous Ap horizon in 1970-71, and then planted with 2+0 bareroot Douglas-fir stock at 6 x 10 ft spacing (1800 stems per hectare). The site remains fully stocked and brush control has been carried out periodically.

The sample population was divided into three sub-populations: 1) trees with no observable occurrences of lammas growth; 2) trees with greater than three occurrences of lammas growth; and 3) trees with between one and three occurrences of lammas growth. Fifteen trees from each of the first two sub-populations were then described and their foliage sampled for laboratory analysis.

Results and Discussion

Analysis of macro- and micronutrient concentrations and contents using analysis of variance and t-tests between means revealed significant differences in four nutrient elements among trees affected and unaffected by lammas growth (Table 7). Trees with lammas shoots had significantly greater foliar concentrations of N ($p<0.03$), Cu ($p<0.01$), Zn ($p<0.03$), and active Fe ($p<0.05$), and lower concentrations of Mg ($p=0.01$), than did trees without lammas shoots. All nutrient elements except Mg appeared to be in adequate or more than adequate supply in both affected and unaffected trees.

As a consequence of the selection criteria used to differentiate each group, branching characteristics were also significantly different between the two populations. Affected trees had more branches per whorl, double whorls and forks and, despite their poor growth form, were usually taller and had larger diameters (Table 8).

Despite a small population size it is felt that a number of tentative conclusions can be drawn from the results. As mentioned above, amendments

TABLE 7. Mean macro- and micronutrient concentrations[1] and mean needle length and weight per 100 needles of the current year's foliage of Douglas-fir affected and unaffected by lammas growth

Sub population	Needle length (mm)	Weight/100 needles (mg)	N	P	Ca	Mg	K	S	Al	Cu	Zn	Mn	AFe	B
			(%)							(ppm)				
Affected	27.4 (4.4)	533 (120)	1.68 (.126)	.146 (.031)	.36 (.06)	.07 (.008)	.63 (.105)	.18 (.024)	.05 (.016)	7 (1.2)	35 (15)	293 (94)	57 (10)	28.7 (11.2)
Unaffected	27.2 (3.3)	561 (100)	1.59 (.121)	.149 (.025)	.333 (.08)	.08 (.002)	.67 (.095)	.18 (.018)	.05 (.007)	6 (.1)	27 (4)	316 (62)	51 (8)	27.1 (6.2)

[1] Standard deviations are in parentheses.

TABLE 8. Stem form and branching characteristics[1] of trees affected and unaffected by lammas growth

Subpopulations	Height (cm)	DBH (cm)	Whorl[2] 1	Whorl 2	Whorl 3	Whorl 4	Whorl 5	Double whorls	Total forks	Forked trees
Affected	722 (89.3)	93.2 (20.9)	4.6 (1.2)	6.8 (2.5)	7.7 (3.0)	6.5 (2.8)	6.1 (1.7)	28	16	10
Unaffected	690 (89.0)	81.4 (15.7)	4.2 (1.1)	5.3 (1.2)	5.2 (1.9)	5.5 (1.2)	5.7 (1.8)	0	0	0

[1] Standard deviations are in parentheses.
[2] Number of primary branches in each of whorls 1 to 5.

of inorganic and organic N-containing fertilizers to the soil normally results in a significant increase in lammas growth. The affected trees in this study, although not under the influence of fertilizers, did show significantly higher N levels. This was also found in a separate study which used composite sampling techniques to examine differences between trees affected and unaffected by lammas growth on four plantations in the Nimpkish Valley (see page 24).

Variability in distorted growth symptoms among individual trees on the same site can be striking, and may be due to microsite differences in soil moisture and nutrient levels. In this study, however, soil variability should not be too great because of the uniformity of the study site. Planting quality and its influence on root development may also be responsible for some of this within-site variability. Additionally, some of this variability is probably due to genetic differences between individual trees.

STAND DENSITY AND GROWTH FORM

Stand density manipulation can make a major impact on individual tree size, stand yield, and wood quality. Branch number and size in relation to initial spacing and subsequent stand density have been examined for many tree species in numerous studies (e.g., Evert 1971; Kramer et al. 1971; Kern 1973; Hattemer et al. 1977; Smith 1983; van Laar 1978; Kent and Unfried 1980; Varmola 1980; Haveraaen 1981; Nelson et al. 1981). In most of these studies branch number as well as branch size have increased with decreasing stand density. Few studies, however, have examined the effects of stand density on other aspects of stem form and wood quality, and these have often produced contradictory results (Muacek 1969; Smith 1977; Varmola 1980). No studies could be found that examined the influence of stand density on the occurrence of lammas growth, forks in the main stem, stem sinuosity, and swelling of the main stem at branch/whorls.

RELATIONSHIPS BETWEEN GROWTH FORM AND STAND DENSITY IN IMMATURE DOUGLAS-FIR[5]

Introduction

Observations made by the authors during the past 3 years of field work on distorted growth in immature stands in coastal British Columbia have indicated that several features of distorted growth are related to stand density. Stem sinuosity, branch number and persistence, swelling at the branch/stem interface, and lammas growth all appear to increase with more open spacing, especially on high productivity sites. Therefore, it was decided to conduct a study that would examine the effect of stand density on stem form and branching characteristics of Douglas-fir.

Methods

A spacing trial established in 1957 at the University of British Columbia Research Forest (Smith 1983) was found to be suitable for the study. The site was located in the Pacific Ranges Wetter Maritime Coastal Western Hemlock biogeoclimatic variant ($CWHa_2$). At present, the site supports an immature (29-year-old) forest community classified as the Pseudotsuga-Kindbergia seral plant association. The site index of Douglas-fir in the original stand was estimated to be 55 m/100 yr.

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[5]Based on Carter, R.E., I. Miller, and K. Klinka. 1986. Relationships between growth form and stand density in immature Douglas-fir. Submitted for publication in For. Chron.

Initial spacing levels produced different stand densities out of which the following three were selected for this study: 1.8 x 1.8 m, 3.6 x 3.6 m, and 4.5 x 4.5 m (or 6 x 6 ft, 12 x 12 ft, and 15 x 15 ft). These levels correspond to 3000, 750, and 480 trees per hectare (or 1250, 310, and 200 trees per acre), assuming no mortality. No density control or tending measures, except for cleaning and brushing, had been carried out.

Each spacing level in the trial consisted of 49 trees in two 7 x 7 tree blocks. Variable spacing resulting from edge effects between treatments was reduced by only considering the central core of 25 trees in each block. Thirty trees were randomly sampled from each of the three spacing levels across two replicated blocks.

Height, dbh, height at the base of the live crown (BLC), diameter at BLC, and age at BLC were measured on each tree. At each of whorls 6 to 10 (counted from the bottom of the tree), the number of primary and secondary branches was tallied and average diameter of primary branches 5 cm from the main stem was determined. Double whorls resulting from lammas growth were tallied separately as two whorls occurring in the same year, with separate counts of primary and secondary branches for each.

The incidence of crooks, forks, ramicorn branches (RB), and lammas whorls (LW) was tallied for each tree, both by total number and age of occurrence. Each tree was also given a subjective index of distorted growth (DGI) based on measured characteristics as well as stem sinuosity, taper, crown form, and foliage vigour. This index ranged from 1, signifying no or very few undesirable form traits with minimal deviation from excellent form, to 5, signifying multiple undesirable branching and form characteristics.

Two variables were calculated. The first was a ratio calculated by dividing the stem diameter measured with calipers, at the centre of each whorl by the mean of the stem diameters measured 2 cm above and below each whorl (WSR). This provides an index of relative stem swelling at each of the five whorls measured. The second is a measure of the absolute increase in diameter due to swelling at each whorl (ΔSD). This variable was calculated by subtracting the mean of the stem diameter measured 2 cm above and below each whorl from the diameter measured at the centre of each whorl.

In total, 59 measurements were made on each tree. Statistically significant differences in these variables among spacing levels and blocks were examined using two-way analysis of variance. The subjective distorted growth index was analyzed with contingency tables.

Results and Discussion

Table 9 gives mean values for each variable of each density and block.

TABLE 9. Stem form and branching characteristics[1] of Douglas-fir grown at three stand densities replicated across two blocks (A and B)

Growth characteristic	Initial spacing and block					
	1.8 x 1.8	1.8 x 1.8	3.6 x 3.6	3.6 x 3.6	4.5 x 4.5	4.5 x 4.5
Height (m)	19.1 (2.89)	19.3 (2.90)	22.3 (1.29)	19.9 (1.73)	22.1 (1.69)	21.7 (0.90)
DBH (cm)	16.9 (5.13)	17.1 (4.88)	30.3 (3.33)	26.5 (5.46)	33.8 (6.57)	32.7 (5.39)
Height at BLC (m)	11.9 (0.98)	11.4 (0.85)	11.2 (0.95)	10.1 (0.86)	9.3 (1.12)	9.7 (1.36)
Diameter at BLC (cm)	11.5 (4.53)	12.0 (4.23)	21.1 (3.35)	19.0 (4.19)	24.6 (5.16)	24.3 (2.75)
Age at BLC	15.5 (1.34)	15.3 (1.37)	13.4 (0.98)	13.7 (0.72)	11.9 (1.28)	12.5 (1.50)
DGI (1-5)	2.3 (0.7)	2.9 (1.2)	3.1 (0.8)	2.4 (0.7)	3.1 (1.2)	3.7 (1.5)
No. of forks	0.1 (0.3)	0.0 (0.0)	0.1 (0.3)	0.1 (0.3)	0.3 (0.7)	0.1 (0.3)
No. of LW's	1.3 (0.9)	0.2 (0.5)	2.1 (1.5)	1.7 (.09)	2.7 (2.2)	3.4 (1.9)
No. of RB's	1.8 (1.8)	1.5 (1.7)	2.7 (1.6)	1.4 (1.5)	2.0 (2.6)	2.9 (1.6)

[1] Standard deviations are in parentheses.

Tree height, dbh, height to BLC, and stem diameter were significantly different between density levels ($p<0.01$). These variables show that differences in tree development (mainly in individual tree size and live- crown ratio) do occur as a result of different spacing levels.

Three variables describing stem form were significantly different among spacing levels (Table 10). These were the DGI, LW, and ΔSD; each increased with decreasing density ($p<.01$). The WSR was not significantly different among density levels. This is the result of stem diameter increasing proportionally with stem swelling, resulting in fairly constant ratios.

The total number of branches per whorl, as well as the number of primary branches per whorl, increased significantly with decreased density for whorls 6 to 8. Whorl 10 showed an increase in primary branches only, while whorl 9 showed no significant differences in branch numbers. Total branch number increased further as density decreased because of the increased occurrence of double whorls.

Average branch diameter in all whorls increased with decreasing density. The mean branch diameter for the 1.8 m spacing level was 1.64 cm while the average for the 4.5 m spacing was 2.94 cm.

When considering all stem and branching characteristics, it appears that wider spacing levels such as 4.5 x 4.5 m (480 seedlings per hectare) produce stems with significantly greater numbers of large, persistent knots. Live branches persist longer in these more open stands (lower live crown and high live-crown ratio) and have greater diameters, thereby lengthening the period of time required before branch mortality, branch decay, and self-pruning. This larger live crown also increases the volume of juvenile wood.[6] The increase in stem diameter due to swelling at branch nodes in more open stands also increases the period of time before clear wood is produced over branch nodes. Therefore, stand density not only affects stand volume and piece size but also several important attributes of wood quality.

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[6] Juvenile wood is the inner core of wood formed under the direct influence of the live crown. The quantity of juvenile wood produced is largely controlled by the size and vigour of the live crown. In general, the first 10 to 15 annual rings of wood throughout the stem have juvenile characteristics (Daniel et al. 1979).

Juvenile wood has a low specific gravity, low cellulose content, short tracheids, more spiral grain, and more compression wood. It is soft, weak, and usually full of small knots. Because of poor fibre characteristics it is also subject to warping and fractures when dried. Juvenile wood has low utility for almost all purposes.

TABLE 10. Stem form and branching characteristics[1] of Douglas-fir grown at three stand densities for whorls 6 to 10 replicated across two blocks (A and B)

Growth characteristic	Initial spacing and block					
	1.8 x 1.8	1.8 x 1.8	3.6 x 3.6	3.6 x 3.6	4.5 x 4.5	4.5 x 4.5
Whorl 6						
Number of branches	6.5 (1.13)	6.5 (0.92)	7.3 (0.91)	7.2 (2.01)	7.6 (1.50)	10.1 (2.02)
Branch diameter (cm)	1.6 (0.23)	1.47 (0.41)	2.44 (0.40)	2.52 (0.55)	2.73 (0.62)	2.63 (0.48)
WSR	1.07 (0.03)	1.08 (0.02)	1.08 (0.03)	1.06 (0.03)	1.08 (0.04)	1.08 (0.03)
ΔSD (cm)	1.09 (0.03)	1.30 (0.02)	2.20 (0.04)	1.57 (0.03)	2.26 (0.05)	2.10 (0.04)
Whorl 7						
Number of branches	6.0 (1.27)	7.0 (1.41)	7.6 (1.22)	7.3 (2.21)	7.5 (1.26)	11.1 (2.56)
Branch diameter (cm)	1.69 (0.31)	1.48 (0.40)	2.52 (0.41)	2.59 (0.58)	2.83 (0.74)	2.91 (0.54)
WSR	1.08 (0.04)	1.09 (0.03)	1.09 (0.02)	1.06 (0.04)	1.08 (0.03)	1.10 (0.02)
ΔSD (cm)	1.12 (0.03)	1.33 (0.03)	2.37 (0.04)	1.54 (0.04)	1.95 (0.05)	2.72 (0.04)
Whorl 8						
Number of branches	7.1 (1.83)	7.2 (1.69)	7.1 (1.70)	7.8 (1.82)	7.3 (1.65)	8.5 (2.02)
Branch diameter (cm)	1.67 (0.29)	1.62 (0.36)	2.68 (0.37)	2.70 (0.47)	3.06 (0.59)	2.88 (0.66)
WSR	1.07 (0.03)	1.11 (0.02)	1.08 (0.03)	1.08 (0.04)	1.09 (0.04)	1.06 (0.04)
ΔSD (cm)	1.12 (0.03)	1.61 (0.03)	2.17 (0.04)	2.0 (0.05)	2.62 (0.05)	1.76 (0.05)
Whorl 9						
Number of branches	6.2 (1.71)	6.6 (1.71)	6.0 (1.64)	6.5 (2.26)	6.9 (1.27)	8.0 (2.54)
Branch diameter (cm)	1.75 (0.45)	1.61 (0.44)	2.72 (0.45)	2.74 (0.56)	3.24 (0.77)	2.96 (0.97)
WSR	1.07 (0.03)	1.09 (0.04)	1.08 (0.03)	1.09 (0.05)	1.08 (0.04)	1.07 (0.03)
ΔSD (cm)	1.02 (0.02)	1.28 (0.04)	1.94 (0.04)	1.89 (0.06)	2.05 (0.06)	1.84 (0.04)
Whorl 10						
Number of branches	6.0 (0.92)	6.2 (1.42)	6.7 (1.88)	6.7 (1.18)	6.1 (2.02)	7.5 (2.00)
Branch diameter (cm)	1.66 (0.45)	1.80 (0.49)	2.77 (0.49)	2.71 (0.44)	3.08 (0.78)	3.03 (0.65)
WSR	1.05 (0.02)	1.09 (0.03)	1.08 (0.04)	1.07 (0.03)	1.07 (0.04)	1.06 (0.03)
ΔSD	1.69 (0.02)	1.20 (0.03)	1.92 (0.05)	1.53 (0.04)	1.76 (0.05)	1.56 (0.04)

[1] Standard deviations are in parentheses.

TREE NUTRITION

Relationships between distorted growth and tree nutrition have been studied in the Vancouver Forest Region since 1981. This chapter examines distorted growth symptoms apparently associated with nutrient deficiencies and imbalances, and presents the results of a fertilizer trial. Symptoms of distorted growth apparently attributable to micronutrient deficiencies can occur as early as 2-3 years after planting or, more often, when the trees are 12-16 years old. The most prominent symptoms are dieback and discoloration of the leader, swelling of the leading shoots, multileadered and bushy crowns, and crooking and curling of the leader; the latter may be the result of several alternative causes.

Micronutrient deficiencies and their effect on growth will require considerable further study before an adequate understanding of their occurrence can be gained. Fertilizer trials must also continue to be studied to assure that diagnosis, prescription, and treatment of these deficiencies will be made with confidence in the future.

RELATIONSHIPS BETWEEN DISTORTED GROWTH AND FOLIAR NUTRIENT STATUS[7]

Introduction

Nutritional problems, deficiencies of B and Zn in particular, have been tentatively diagnosed as the cause of specific distorted growth symptoms in several immature stands of Douglas-fir, western hemlock, and Pacific silver fir.

Methods

Stands displaying distorted growth symptoms thought to result from nutrient deficiencies were located by government and industrial foresters and were sampled during 1981 and 1982 (Figure 23). Vegetation, site features, and specific visual symptoms of distorted growth were described for 43 Douglas-fir plantations (5 to 32 years old) and one naturally established stand of western hemlock and Pacific silver fir (29 years old). Almost all stands were located in the Wetter subzone of the Coastal Western Hemlock biogeoclimatic zone. Five extremely vigorous Douglas-fir stands

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[7] Based on Carter, R.E., A.M. Scagel, and K. Klinka (1986).

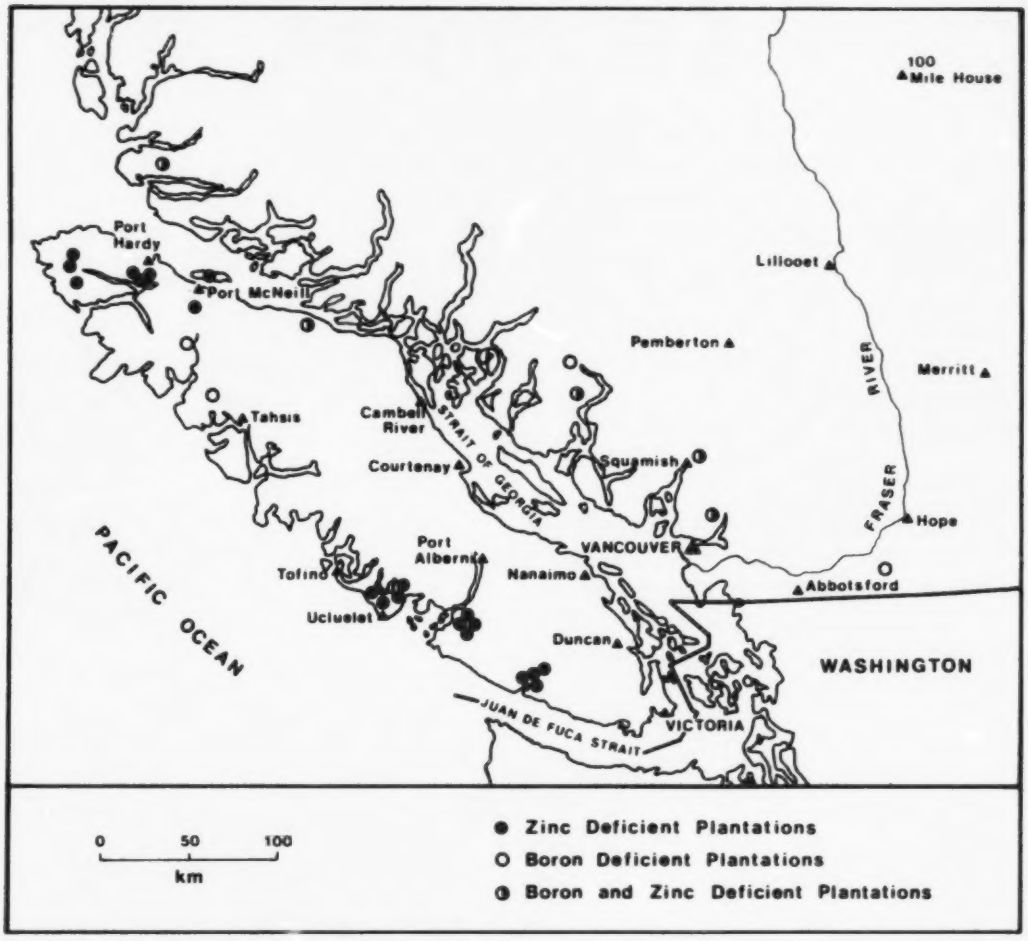

FIGURE 23. Location of the 44 stands sampled for the nutrition study.

(60 to 73 years old; site index at 100 years > 65 m) located in the CWHa subzone were also described (Klinka et al. 1981). These vigorous stands all had excellent stem form and branching characteristics and were used in this study as benchmarks for comparative purposes.

Results and Discussion

Foliar analysis indicated that apparent deficiencies of B and Zn are more widespread than was commonly thought. Of the 43 Douglas-fir plantations studied, 16 had mean B levels in the current years foliage of < 12.0 ppm (possible upper boundary for marginal B deficiency in Pinus radiata [Lambert and Turner 1977]). Thirteen of these plantations had foliar B concentrations of < 8.0 ppm, and seven plantations had foliar B < 5.0 ppm,

suggested as being severely deficient levels for other species (Lambert and Turner 1977; Aronsson 1983). Forty-one stands had foliar Zn concentrations < 15.0 ppm, 32 had foliar Zn levels < 12.0 ppm, and 17 had foliar Zn levels < 9.0 ppm, tentative boundaries for slight, moderate, and severe deficiencies, respectively (Ballard and Carter 1986).

Table 11 compares mean foliar nutrient concentrations of stand(s) having B < 5.0 ppm and Zn < 9.0 ppm to the mean value of the five benchmark stands mentioned previously. Foliar concentrations of Ca ($p < 0.01$), Mg ($p < 0.01$), sulphate-S ($p < 0.01$), Zn ($p < 0.05$), and B ($p < 0.01$) were significantly higher, and N ($p < 0.05$), Mn ($p < 0.05$), and Al ($p < 0.01$) significantly lower in the benchmark stands than in the stands with low foliar B levels. The stands with low foliar Zn levels were significantly lower in P ($p < 0.05$), Ca ($p < 0.05$), and sulphate-S ($p < 0.01$), and higher in Mn ($p < 0.01$) and Al ($p < 0.01$) than in the benchmark stands.

The naturally established stand of western hemlock and Pacific silver fir displayed multiple leaders caused by repeated dieback. Both species had very low foliar concentrations of B (< 7.0 ppm), while Zn levels in Pacific silver fir (11.0 ppm) were slightly higher than in western hemlock (< 6.6 ppm).

In the five stands where naturally established western hemlock was sampled along with planted Douglas-fir, Douglas-fir was found to have foliar B levels approximately 55.3% lower and foliar Zn levels approximately 45.6% higher than western hemlock. This suggests that these two species have differential abilities to take up and/or retain these nutrients in their foliage.

Most Douglas-fir stands apparently deficient in B and/or Zn were established following clearcutting and broadcast burning. Stands with low foliar B levels are most common on lower slopes and valley bottoms (0-870 m) on soils derived from base-poor parent materials (quartz- and granodiorites), particularly on soils of fluvial origin. The soils were generally coarse-textured (gravelly sandy loams or loamy sands). Soil moisure and nutrient regime ranged from fresh to moist and nutrient-medium to -rich, respectively. Low levels of Ca, Mg, and sulphate-S were commonly associated with low foliar B levels. These low foliar Ca and Mg levels are likely due to the low base saturation of soils usually associated with B deficiency and high leaching losses.

Douglas-fir stands with low foliar Zn levels were found on a broad range of site types from sea level to 980 m. They were common on coastal lowland sites with soils derived from glacial marine deposits and glacial tills of mixed lithology. Soil texture ranged from gravelly-loamy sands to fine loamy clays. Soil moisture and nutrient regimes ranged from moderately dry to moist and nutrient-poor to -very rich.

TABLE 11. Mean foliar nutrient concentrations[1] in Douglas-fir stands showing low levels of boron and zinc together with those of the benchmark stands

Apparent deficiency	Sample size	N	P	K	Ca	Mg	S	SO_4	AFe	Mn	Cu	Zn	Al	B
		(%)						(ppm)						
B[2]	7	1.43 (.098)	.174 (.050)	.586 (.179)	.281 (.118)	.095 (.016)	.129 (.018)	46.8 (12.4)	29.8 (5.2)	292 (148)	4.4 (1.5)	13.1 (5.7)	245 (94.7)	4.3 (1.1)
Zn[3]	17	1.36 (9.15)	.134 (.026)	.627 (.134)	.263 (.418)	.108 (.014)	.124 (.016)	74.1 (18.6)	47.4 (12.8)	316 (164)	3.9 (1.0)	8.1 (2.1)	300 (93.3)	14.3 (5.3)
Benchmark stands	5	1.38 (.07)	.168 (.032)	.608 (.122)	.340 (.041)	.127 (.021)	.125 (.017)	239 (67.7)	37.5 (18.1)	186 (54)	4.4 (1.5)	18.4 (3.8)	115 (42.4)	13.2 (3.2)

[1] Standard deviations are in parentheses.

[2] Boron levels < 5 ppm.

[3] Zinc levels < 9 ppm.

The presence and high cover of Rubus spectabilis, Sambucus racemosa, Epilobium angustifolium, Athyrium filix-femina, Polystichum munitum, Galium triflorum, and Mycelis muralis were interpreted to indicate high N-mineralization levels. This inferred high availability of soil N combined with high growing season precipitation, often results in exceptional growth rates in young plantations, thereby increasing nutrient demand. Simultaneously, soil B and Zn reserves may be low because nutrients previously held in now absent or reduced surface organic horizons may have been lost from the soil-plant system through leaching and, when fires are very hot, volatilization. Therefore, dilution (Morrison 1974) may aggravate or induce deficiencies and/or near deficiencies of B and/or Zn.

Lambert and Turner (1977, 1978) suggest that B and S deficiencies in Pinus radiata often occur together. In this study, total B was positively correlated with total S ($p < 0.01$; $r=0.371$); although total S levels appear to be adequate, sulphate-S levels were often very low (<50 ppm). Sulphate-S had a significant negative correlation with total N ($p < 0.01$; $r=0.518$). Very low levels of sulphate-S in many of the sampled stands suggests that S reserves are often somewhat deficient in relation to N supply.

Uptake of B is primarily through mass flow of water to the roots and is, therefore, strongly influenced by soil moisture (Mengel and Kirby 1982). Zinc uptake is primarily an active process which is not as strongly influenced by soil moisture. However, in acid sandy soils Zn concentrations may be very low and diffusion gradients with root depletion zones may occur (Nambiar 1974; Mengel and Kirby 1982). Resampling in 13 stands in October 1983, and October/November 1984, indicated that foliar B and Zn levels are subject to wide temporal variations (Table 12). This temporal variation is likely the result of substantial differences in growing-season precipitation. Precipitation in May and June, a period of high nutrient uptake and demand, was very low in 1982 relative to 30-year normals (Canadian Climate Program [Table 13]), while it was quite high in 1983. This suggests that deficiencies of B and/or Zn are acute rather than chronic with the occurrence of periodic acute deficiencies being influenced by growing-season soil moisture supply.

In summary, visual symptoms, site conditions, and foliar nutrient relationships associated with apparent B- and Zn-deficient stands in the Vancouver Forest Region were very similar to those described by Australian and Scandinavian workers. Critical foliar concentrations for micronutrients established by researchers examining other species appears to relate quite well to Douglas-fir. Visual symptoms of apparent B deficiencies become most obvious when foliar concentrations are less than 5.0 ppm. Visual symptoms of apparent Zn deficiencies only become obvious at very low levels, i.e., less than approximately 9.0 ppm.

TABLE 12. Mean foliar B and Zn concentrations[1] for 13 Douglas-fir stands sampled in 1982 and 1983

Year	Boron (ppm)	Zinc (ppm)
1982	9.5 (3.1)	11 (2.9)
1983	16.4 (6.8)	25 (7.3)

[1] Standard deviations are in parentheses.

TABLE 13. Mean annual and monthly precipitation of 15 climate stations in the CWHb subzone (from Canadian Climate Normals 1982)

Year	Mean ann. ppt.	Mean monthly precipitation				
		April	May	June	July	August
30-year normal	2340	138.7	99.6	94.0	65.5	78.9
1982	2379	204.3	43.2	45.3	156.7	105.4
1983	2447	123.5	89.5	153.3	247.3	50.1

BRITTAIN RIVER FERTILIZER TRIAL: THIRD-YEAR RESULTS[8]

Introduction

A fertilizer trial was established in four 30-year-old stands in the early spring of 1982: two stands of plantation grown Douglas-fir, and two of naturally established western hemlock. Both species showed symptoms of severe leader dieback and poor stem form (Carter et al. 1984). Foliage retention and vigour in Douglas-fir was also very poor. The main objective of this trial was to determine whether a significant reduction in the incidence of distorted growth characteristics such as leader dieback and poor foliage vigour and retention could be gained through corrective fertilization. The secondary objective was to test the effectiveness of several inorganic fertilizers at increasing foliar concentrations of all nutrients to optimum levels determined by foliar analysis.

Methods

This trial used a fixed plot design. Twenty-six 0.02-ha plots were established; nine in each of the Douglas-fir plantations and four in each of the western hemlock stands. Eight trees were measured and sampled in each plot. The eight fertilizer treatments are given in Table 14.

Each year following treatment, foliage was sampled from each tree and current and previous year's shoot length were measured from two branches on opposite sides of the third whorl. The incidence of leader damage (e.g., dieback, breakage, lammas shoots, and unknown deformities) and changes in foliage size and color were recorded for each tree.

Results and Discussion

Uptake of B in the treatment plots was satisfactory. Initial foliar concentrations were slightly high in the Boron-3 treatment and slightly low for the Boron-1 treatment. Foliar B concentrations for all three levels stabilized at more optimal concentrations after the first growing season (Table 15). No observable change in foliar Mg, K, or S levels occurred as a result of fertilizer applications of these nutrients. However, visual differences in foliage retention and colour were striking in plots treated with Boron-1, Boron-2, Boron-3, Boron-1 $MgSO_4$, and Boron-2 $MgSO_4$

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[8] Based on Klinka, K. and R.E. Carter (1985). Rehabilitation of second-growth plantations showing distorted growth in the Coastal Western Hemlock biogeoclimatic zone. Annual Res. Rpt. to Science Council of B.C.

TABLE 14. Design of the Brittain River fertilizer trial

Location	Tree species	Fertilizer treatments
A, B	Douglas-fir	Control
A,B	Douglas-fir	Boron-1 (1.0 kg B/ha)
A,B	Douglas-fir	Boron-2 (2.0 kg B/ha)
A,B	Douglas-fir	Boron-3 (3.0 kg B/ha)
A,B	Douglas-fir	Boron-1; $MgSO_4$ (40 kg Mg/ha)
A,B	Douglas-fir	Boron-2; $MgSO_4$
A,B	Douglas-fir	Boron-1; K_2SO_4 (50 kg S/ha)
A,B	Douglas-fir	$MgSO_4$
A,B	Douglas-fir	K_2SO_4
C,D	western hemlock	Control
C,D	western hemlock	Boron-1
C,D	western hemlock	Boron-2
C,D	western hemlock	Boron-3

[1] All fertilizers were ground applications applied by hand.

[2] B was applied as Solubor (20.5% B), $MgSO_4$ as epsom salts (11% Mg, 14% S), and K_2SO_4 as a salt (50% K, 14% S).

(Figure 24). Foliage in these treated plots was usually much darker green with far less chlorosis and necrosis. This response was extremely variable among trees both within and among treatments.

Three growing seasons after fertilization no significant reduction in leader dieback and/or stem deformities can be shown. The nature of the stand and tree structure in the trial plots preclude simple measurement of these characteristics. Many trees already had two to seven main stems and/or leaders in the upper crown, often with a high degree of variability in the incidence, severity, and causes of dieback symptoms within individual trees. Additionally, Armillaria mellea had begun to cause high levels

TABLE 15. Needle length, weight, and foliar boron concentrations 1, 2, and 3 years after application of fertilizer treatments

Treatment	Tree species	Location	Needle length (mm)			Weight/100 needles (mg)			Boron (ppm)		
			1982	1983	1984	1982	1983	1984	1982	1983	1984
Control	Fd[1]	A	25.0	28.7	24.0	464	606	518	3.4	6.0	7.0
		B	24.5	25.0	27.8	411	470	513	3.5	6.0	9.0
	Hw[2]	C	11.0	13.5	10.8	303	337	283	7.3	11.0	15.0
		D	13.6	13.7	12.4	308	349	262	6.7	8.0	8.0
Boron-1	Fd	A	22.9	25.1	27.7	368	571	520	11.6	23.0	17.0
		B	22.6	24.4	25.7	386	486	528	21.3	24.0	22.0
	Hw	C	12.6	13.6	9.93	270	281	193	33.8	29.0	22.0
		D	11.5	16.5	11.5	240	347	292	43.1	25.0	22.0
Boron-2	Fd	A	25.2	24.3	25.8	460	496	445	16.0	20.0	17.0
		B	24.2	26.6	21.5	476	574	468	27.3	24.0	21.0
	Hw	C	12.3	14.2	11.8	276	331	202	39.8	33.0	23.0
		D	13.1	12.1	11.6	277	431	296	46.4	26.0	28.0
Boron-3	Fd	A	23.9	25.4	25.6	426	517	457	30.1	33.0	30.0
		B	24.9	24.4	24.6	447	532	485	58.4	28.0	22.0
	Hw	C	12.8	14.4	9.4	276	326	220	59.0	41.0	31.0
		D	12.2	12.9	11.7	263	339	262	59.6	39.0	23.0
B-1, $MgSO_4$	Fd	A	22.7	22.6	26.3	414	375	515	19.1	24.0	21.0
		B	23.1	23.9	27.2	396	515	450	13.8	20.0	19.0
B-2, $MgSO_4$	Fd	A	23.4	26.1	26.7	395	563	551	16.3	18.0	23.0
		B	24.9	25.4	29.4	473	539	685	38.4	27.0	26.0
B-1, K_2SO_4	Fd	A	21.1	24.7	25.0	320	430	465	20.0	19.0	19.0
		B	25.8	24.9	27.3	477	433	636	20.1	20.0	19.0
$MgSO_4$	Fd	A	25.6	25.6	23.5	458	585	451	3.9	5.0	9.0
		B	26.2	25.4	26.0	536	489	484	3.4	9.0	8.0
K_2SO_4	Fd	A	25.0	25.2	25.5	480	619	446	3.4	7.0	8.0
		B	21.8	28.0	28.3	399	699	741	3.1	7.0	6.0

1 Douglas-fir.

2 Western hemlock.

FIGURE 24. Foliage size and vigour in Douglas-fir 2 years after application of the Boron-2 fertilizer treatment.

of mortality in many of the plots, leaving only seven plots with a full complement of eight trees. This complexity, combined with logistic difficulties associated with observing leader characteristics in these older trees will continue to make statistical evaluation of these characteristics very difficult.

Boron applied 2-3 kg/ha appears to result in adequate foliar B concentrations that show promise of being maintained for at least 5 years after application. Two growing seasons may be required before foliar B reaches adequate levels where B is applied at only 1.0 kg/ha. The 3.0 kg B/ha rate resulted in foliar concentrations as high as 120 ppm, close to possible toxicity levels (Stone 1968); however, foliar B levels stabilized between 12 and 50 ppm within 1 year.

The failure of applications of inorganic fertilizers containing Mg, K, and S to increase foliar concentrations is not fully understood. These fertilizers have been used successfully by other researchers on other sites (Leaf 1968). These elements may have been subject to considerable leaching losses due to the low cation exchange capacity and pH of these soils and the high annual rainfall in the Brittain River valley (approximately 3000 mm/year).

Interpreting results of the Brittain River fertilizer trials has been made difficult by the extent of damage already present before establishment of the trials and by the increasing presence of Armillaria mellea. Douglas-fir in this valley may be in a weakened physiological condition as a result of the advanced nature of distorted growth symptoms, possibly precluding rehabilitation. However, improved foliar retention and vigour in response to B fertilization indicates a good potential for overcoming distorted growth symptoms induced by micronutrient deficiency.

GENETIC ASPECTS OF DISTORTED GROWTH

The expression of each growth form trait in all tree species is controlled by both genetic and environmental factors. Tree improvement programs can identify the amount of the total variation in the expression of each growth form trait that is under genetic control, and estimate potential genetic gains that can be made through selection and breeding. These programs can also be used to identify the role played by individual environmental factors in determining growth performance.

In simple terms the potential for improving growth form through genetic selection is determined by five factors:

1. the amount of natural variation in each trait's expression in wild populations;

2. the amount of this total natural variation that is under direct genetic control (trait heritability);

3. the intensity of selection for each trait within the population being sampled;

4. correlations between traits; and

5. the stability of each trait's expression when grown over a range of sites.

When combined with trait heritability and selection intensity, the amount of natural variation in each trait's expression in wild populations sets theoretical limits on the genetic gain that can be attained from each generation in a breeding program. Correlations between traits set practical limits on the number of traits to be selected, while trait stability is important when ranking growth performance of individual families over a range of site conditions.

Selection for the improvement of several traits such as stem sinuosity, branch number, branch angle, lammas growth, etc. is made difficult because many desirable traits are either negatively correlated with one another or are inherited independently. If two traits are positively correlated (i.e., improvement of one trait results in simultaneous improvement of another), multiple trait selection may be possible through the selection of a single trait. If two traits are negatively correlated, selection for one will result in concomitant selection against the other. If the traits are not correlated, selection for one results in no selection for the other(s), requiring independent selection for each trait. This results in exponential increases in the sampling intensity required in the selection process.

The stability of each trait's expression within a breeding family must also be determined over a wide range of environmental conditions before it is selected for commercial seed production. A family that has been selected on the basis of its growth performance under one set of environmental conditions may be ranked very differently under different environmental conditions.

Therefore, the costs involved with selection and evaluation of growth form traits in a large number of families over a wide range of sites restricts the number of traits to be improved. The choice of traits for selection must be narrowed down to one or a few traits in which genetic improvement will give the greatest economic benefit (Campbell 1964).

Most growth form traits in Douglas-fir have moderate to low heritabilities, with environmental factors such as climate, soil moisture, and soil nutrient status accounting for a large component of the total variation in each trait's expression. Undesirable correlations between several growth form traits such as stem sinuosity, frequency of lammas growth, branch number, diameter, and length, and tree height and diameter growth have also been identified (Campbell 1961; Jarret 1979; Birot and Christophe 1983). Therefore, a great deal of time and research will be necessary before a reduction in the occurrence of distorted growth characteristics will result from tree improvement programs. However these programs are essential if both environmental and genetic factors controlling growth performance are to be understood at a level that can be used in their practical application.

STAND MANAGEMENT

To place the overall distorted growth problem in a management perspective, the area of stands affected and causes of undesirable growth form and/or growth performance must be determined. The principal causes have been outlined in the previous chapters. The geographic area affected remains open for debate, as the definition of when the symptoms constitute a problem is very dependent on the desired use of the future crop. Bud damage, leader breakage and dieback, forking, and sinuosity of the main stem are attributed to several causes including damage by insects, birds, frost, snow, wind, sunscald, nutrient deficiencies, lammas growth and herbicides. Branching characteristics and stem form at branch internodes, as well as forking and sinuosity, have been suggested to vary in response to the frequency and pattern of lammas growth, growth rate, stand density, and genetic variation among individual trees.

Silviculturists can influence wood quality through genetic selection and by treatments that affect live-crown ratio, growth rate, and branching characteristics of trees in a stand, i.e., by control of initial and subsequent stand density regime, pruning, and fertilization. The effect of stand density on wood quality is vastly more important than any other variable. Stand density manipulation has a major impact on individual tree size and stand yield; furthermore, through control of stand density, the silviculturist can influence stem form, knot size, branch persistence, and the volume of juvenile wood.

In most stands showing distorted growth symptoms only a small fraction of the trees (usually between 5 and 10%) are affected. Individual distorted growth symptoms can occur repeatedly or in combination with other symptoms within a tree, resulting in a cumulative reduction in stem form quality; or individual distorted growth symptoms may occur in separate trees, resulting in an increase in the percentage of affected trees within a stand. The number of trees in a given stand that are seriously affected by leader dieback, lammas growth, multiple leaders, and forks, as well as excessive branch number, size, and persistence, must be considered in relation to stand age, density, the number of trees to be removed during spacing and thinning operations, and the number of trees constituting the final crop. The distribution of affected trees within the stand must also be considered. The highest incidence of affected trees is often found along roadsides resulting in an over-estimation of the occurrence and severity of distorted growth problems when viewed from the road. Trees showing distorted growth symptoms may also have an uneven distribution in the stand, possibly reflecting microsite variation. This pattern must also be recognized so that rehabilitative treatments can be applied where they will have the greatest impact.

As indicated in the introduction, a silviculturist should approach distorted growth problems in the following sequence:

1. Decide when symptoms of distorted growth constitute a problem (i.e., how many trees have serious distorted growth problems and what is their distribution in the stand);

2. Identify the factors responsible for the problem(s);

3. Identify the management options currently available for treatment of the problem(s); and

4. Determine the best management option for each situation.

The following sections provide preliminary information on management options currently available for dealing with distorted growth problems.

SELECTION OF TREE SPECIES, PROVENANCE, AND PROGENY

Species, provenance, and progeny of forest trees are all adapted to a certain range of site conditions. Within this range, growth performance primarily depends on site quality and stand conditions in which the trees are growing. On sites unsuited for the chosen species, provenance, or progeny, growth potential may not be realized, susceptibility to damaging agents may increase, and more effort will be required to establish and grow the new forest stand. Sound forest management applies a site-specific approach which considers the performance of tree species, provenances, and, in the future, the genetic structure of individual trees (progeny).

The importance of adopting a site-specific approach to tree species selection has recently become much better understood, especially in view of failures in reforestation and, even more recently, the unsatisfactory performance of many immature Douglas-fir stands. While regeneration failures can often be rectified, problems affecting growth form may persist and/or increase with age, possibly having a far-reaching influence on the stands' future utility. An example can be found in the Brittain River Valley, where improper species selection has exaggerated nutritional problems inherent to the site, to the point where the trees are no longer productive, and drastic rehabilitation measures are required.

One of the most common and easily avoided causes of unsatisfactory growth performace is a poor choice of tree species. Thus, species selection is of fundamental importance in reducing the incidence of distorted growth. Principles used in selecting tree species for regeneration of forest sites in southwestern British Columbia have been discussed by Klinka

and Feller (1984). Guidelines for site-specific tree species selection in the Vancouver Forest Region have been put forward by Green et al. (1984) and Klinka et al. (1984). Tree species selection made on the basis of these guidelines should significantly reduce the incidence of distorted growth in future stands.

In cool, mesothermal climates, undesirable growth form characteristics of Douglas-fir appear to increase with increasing soil moisture, and soil nitrogen availability. The highest incidence of distorted growth has been found on disturbed, moist, and nitrogen-rich soils within the Windward Submontane variant of the Wetter Coastal Western Hemlock biogeoclimatic subzone (CWHb1). Douglas-fir is not suited to either the climatic or edaphic conditions of this variant. This is evidenced by the fact that Douglas-fir plantations on drier soils also have an unusually high occurrence of forks in the main stem, an abundance of heavy branches, and poor form at branch whorls. On many of these sites Douglas-fir was absent or a minor component of the original stands, and is not considered to be a reliable crop species.

Both species and provenance must be carefully considered when planting stock is selected. Silviculturists in western North America have recognized that selection of genetically adapted tree species populations is essential for achieving successful reforestation and optimal growth performance (e.g., Ching and Bever 1960; Haddock 1967; DeBell 1981; Silen 1982). The basis for provenance selection in British Columbia is currently under review.

Growth form characteristics have an important genetic component. Seed production orchards have not yet reached a degree of sophistication where selection of orchard trees is made from progeny whose evaluation of growth performance included growth form and wood quality traits. Therefore, there is little a forest manager can do with regard to selecting the most suitable progeny for a given site. However, it is imperative that a strong demand be placed on breeding programs to select for wood quality traits as well as measures of height and diameter growth currently used in selection.

SELECTION OF STAND TREATMENTS

Forests improperly managed for timber production are commonly too sparsely or too densely stocked with trees. Both extremes have the final effect of reducing the value of the crop produced. The major causes of degrade in immature, fast-growing forest stands are increased volume of juvenile wood, reaction wood, spiral grain, forks in the main stem, and excessive branch number, size, and persistence. Maximizing individual tree growth also delays the transition from juvenile to mature wood. All

characteristics associated with desirable wood quality are related to the period of growth following cessation of juvenile wood production, at the position in the tree where wood quality is assessed (Smith 1962).

On the basis of a site-specific analysis, a silviculturist must decide on the most appropriate treatments for individual stands. Following the choice of tree species and provenance, these decisions may include: site preparation, initial stocking level, and treatments such as spacing, thinning, pruning, and fertilization.

The general management strategy adopted for **Douglas-fir stands on sites with existing or potential distorted growth** considers optimization of both piece size and wood quality. This compromise should provide increased management flexibility in meeting diverse and constantly changing product and production requirements. The general growth strategy adopted for this objective considers less rapid growth early in the rotation through the maintenance of high stocking levels with more rapid growth later in the rotation being brought about through reduction of stocking levels, and the relief of possible growth constraints. Obviously, with increasing age and severity of distorted growth there are fewer options available for rehabilitating stands already showing advanced symptoms of distorted growth.

Stand Density, Spacing, and Pruning

Plantations established at higher densities have the advantage of providing the silviculturist with greater flexibility for responding to changes in management objectives. Thinnings will also provide opportunities for selection of crop trees of the best form. These "high density" stands (approximately 1000 stems per hectare) will have a greater total stand volume early in the rotation due to the greater number of stems; however, as stand development proceeds through crown closure, mortality and smaller piece sizes in the higher density stands will eventually result in the merchantable volume being surpassed by the merchantable volume of lower density stands. If advantages of improved quality -- defined in terms of reduced branch number and size, improved form at branch nodes, stem straightness, and a reduced juvenile wood component -- resulting from high initial stand densities are to be realized without a significant increase in rotation length, these stands must be thinned following natural branch mortality on the lower stem and while the crop trees still have sufficient live crown to vigorously respond to thinning (i.e., greater than approximately 35% of the stem in the live crown).

Thinning(s) carried out later in the rotation (after approximately age 30) should be used to select the final crop trees of the best form and to

maximize their growth rate by progressively reducing stand density until only final crop trees remain. The rate of volume production on a per stem basis will likely be somewhat lower and the rotation age somewhat longer in these initially dense stands than in stands planted at lower initial densities; however, the improved wood quality and increased management flexibility should justify this difference.

Trees planted at a low density will have a greater number of large, persistent knots, increased swelling at branch nodes, and, as a result of their greater live-crown ratio, more conical stem form, and, presumably, a greater proportion of juvenile wood. These trees are also likely to have a greater number of forks and double whorls. Low initial stocking levels reduce both planting and thinning costs while maximizing commercial volume production on crop trees. Disadvantages of low espacement levels include possible increases in weeding costs and reduced management flexibility throughout the rotation. However, if clear wood is a priority, crop trees in these stands must be identified and pruned. Ideally an early pruning to about 2 m should be carried out when the trees are not more than 6 m tall. This pruning should be followed by successive lifts to 6 or 12 m. This will shorten healing time and maximize clear wood production, as radial growth in the pruned portion of the stem will still be relatively high. Research has shown that up to one-third of the live crown can be removed through pruning with no measurable loss of height growth or radial increment (Staebler 1963). This reduction in branch size and persistence will not only increase the period of clear wood production but also reduce the period of juvenile wood production in the live crown.

Whether natural or artificial pruning methods are employed it is essential that a period of rapid radial growth occurs following pruning. Whenever possible, growth constraints should be relieved through the use of thinning and/or fertilization following pruning.

Fertilization

When the economics of nitrogen fertilization is considered along with data on the nutrient status of Douglas-fir in coastal British Columbia, nitrogen fertilization early in the rotation is not recommended. Site preparation practices that increase the availability of soil nitrogen (i.e., prescribed burning) should also be discouraged, particularly on moist nitrogen-rich sites. Practices that result in the removal of the forest floor should also be avoided on sites with coarse and base poor soils of fluvial or glacio-fluvial origin, especially in high-precipitation environments (CWHb subzone). These surface organic horizons represent a significant reserve of available macro- and micronutrients on these sites.

A full evaluation of corrective fertilizer trials established in 1982/83 is yet to be completed. In stands where a severe boron deficiency had been diagnosed as the cause of specific distorted growth symptoms on the basis of visual symptoms and foliar analysis, amendments of boron applied to the soil at the rate of 1, 2, and 3 kg/ha (as Solubor 20.5% B) along with other nutrients have been effective in relieving some of the symptoms. However, micronutrient deficiencies and their effects on growth performance will require further study before diagnosis, fertilizer prescriptions, and treatments of these deficiencies can be made with confidence. In contrast to growth-stimulating fertilization, growth form-correcting fertilization should be applied as soon as symptoms and deficiencies can be confidently diagnosed.

Growth-stimulating fertilization should be considered later in the rotation, in situations where it can be justified by the economic benefits of volume growth response on good quality timber. Stands about 10 to 15 years before rotation age are likely to be the most suitable candidates for treatments. Forest fertilization should be based on the evaluation of stand and soil nutrient status and diagnosis of possible nutrient deficiencies following guidelines developed by Ballard and Carter (1986). In most situations nitrogen is still the nutrient most limiting the growth of Douglas-fir; however, existing deficiencies or nitrogen-aggravated and/or -induced deficiencies of other nutrients (notably boron, magnesium, and sulphur) have also been tentatively diagnosed for fast-growing Douglas-fir stands on high productivity sites. Consequently, effective stand- and site-specific fertilization may have to consider the use of blended fertilizers.

Rehabilitation of Stands Significantly Affected by Distorted Growth

Douglas-fir stands that have a significant number of trees with distorted growth symptoms severe enough to diminish the future commercial viability of the crop must be considered for complete rehabilitation. These stands are usually located on sites where Douglas-fir was absent or was a minor component of the original stand, often in the CWHb1 biogeoclimatic variant. Many sites supporting Douglas-fir stands with severe distorted growth symptoms are very productive sites for the growth of western hemlock, Pacific silver fir and/or western redcedar. The costs of leaving these stands in an unproductive state can be considerable.

Rehabilitation measures include selection of alternative species during thinning(s), fill-in planting with alternative, ecologically appropriate species, or destruction of the existing stand and establishment of an alternative species. Decisions regarding each of these rehabilitative measures should consider:

1. the distribution and vigour of suitable alternative tree species within the stand;
2. the number, size, and condition of existing Douglas-fir trees in the stand; and,
3. the costs of not returning the stand to a productive state.

If the stand has an acceptable number of well-distributed alternative tree species (i.e., western hemlock, Pacific silver fir, western redcedar and/or Sitka spruce), these trees may overtop the Douglas-fir and no rehabilitative action may be necessary. If natural regeneration is not available or is not properly distributed, the possibility of fill-in planting should be considered. If these alternative crop trees are currently suppressed by the Douglas-fir overstory they can be released either by mechanical or chemical thinning of overstory Douglas-fir trees of the worst form.

Late immature Douglas-fir stands showing severe distorted growth symptoms must be examined to determine whether a marginally commercial crop can be taken from the stand. In some cases the value of this crop may offset harvesting costs and help justify the expense of establishing the new crop.

In conclusion, Douglas-fir sensitivity to distorted growth is a function of the genetic structure of the stand, stand density, and site nutrient and moisture regime. Recognition of stands showing a high incidence of distorted growth symptoms, and identification of the causes of these symptoms is the basis for managing these stands. Management strategies that emphasize wood quality and maximize management flexibility and opportunity throughout the rotation offer the most rational approach for dealing with distorted growth problems at this time.

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